SPATIAL DISTRIBUTION OF MAGNETIC FIELD AND ITS MINIMIZATION IN RESISTANCE SPOT WELDING

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Spatial distribution of magnetic field (MF) generated by resistance spot welding machine in the work zone was determined with allowance for its spectral composition. Results of experimental studies of the effect of welding process parameters and distance from current-conducting elements of the welding circuit on the index of exceeding the MF level, according to the current medical requirements, are presented. Recommendations on protection of welders from MF are suggested, which are intended for designers of resistance welding machines, technologists and users of these machines.

Keywords: *resistance spot welding, electromagnetic radiation, index of exceeding magnetic field level, methods of welder protection, shielding magnetic materials, alloy with amorphous structure*

At present resistance welding has become widely accepted in some industries of Ukraine, and it is one of the leading technologies in modern production. There is a large fleet of electrical equipment and machines of various types and purpose with power from several up to hundreds kilovolts per ampere. These are mainly 50 Hz AC machines.

During operation of these machines magnetic fields (MF) of considerable intensity are generated, which is several times higher than the value specified by sanitary codes [1]. MF of such intensity can affect service personnel health, causing certain negative functional changes in the body, because of the effect on cardio-vascular, nervous, urogenital, endocrinal and other systems. In this connection, the need arose to monitor the electromagnetic situation in welder workplaces and to ensure safe labour conditions for them. This problem became more acute with introduction of new norms in Ukraine [2], which specify safety conditions in operation with sources of electromagnetic noise, and take into account modern medical investigations.

At resistance welding pulsed MF are generated in the working zone. In welder work places the main source of these fields is the welding transformer, not completely shielded by the machine case and, as a rule, unshielded high-current elements of the welding circuit (electrodes, plugs, consoles, buses), as well as current-conducting cables and complex-shaped welded items. MF formed at resistance welding in different frequency ranges and general procedure of determination of their levels are described in [3].

The purpose of this work is establishing MF spatial distribution near resistance spot welding machine and determination of the possibilities of minimization of its intensity.

During experiment performance possible resistance spot welding modes were modeled in batch-produced spot welding machine MT-2202 of medium power, taking into account the following considerations.

First, welding modes are determined by welding equipment design and capability of their regulation. For modern resistance spot welding equipment, they are rather wide and envisage the following adjustments of heat input into the welded joint: switching of power stages of welding transformer with thyristor contactor; variation of the duration of pulses of sinusoidal full-phase 50 Hz current in one packet; welding (and heat treatment of welded joint in welding machine electrodes) by several (up to 3) packets of sinusoidal full-phase pulses with regulation of pulse number in packets and pause duration between packets; phase regulation of heating (welding current) in each packet (α_{ph} = 20–180°); modulation of leading and trailing edges of pulse packets, i.e. amplitudes of a certain pulse number from zero up to maximum values.

Secondly, as the instrumentation of welding cycle control supports (permits) these adjustments, welding technologists do not always use them in their work with discretion, and ignore sanitary norm requirements [2].

Investigations conducted at PWI show that for resistance welding radiation in 50–1000 Hz frequency range is the determinant sanitary-hygienic factor at evaluation of MF levels. The least hazardous welding mode, where MF spectrum contains the smallest number of essentially significant harmonic components higher than first harmonic of 50 Hz frequency, mainly determining

MF energy load, is the mode of welding with one packet of sinusoidal full-phase pulses of welding current, having the longest possible duration and the smallest possible amplitude (so-called soft welding mode). It is also established that for this welding mode, considering the sanitary aspect, the number of sinusoidal pulses (periods) of not less than 15 can be taken, i.e. the time of welding one spot should equal to $t_w \geq 15 \cdot 0.02 \geq$ ≥ 0.3 s. It would be convenient to take this welding mode as the reference one, with which other possible modes obtained as a result of hygienic evaluation, could be compared, and comparative analysis could be performed. In real application in production more stringent conditions are preferred. Therefore, stringent mode of welding (1.5 + 1.5) mm samples from carbon steel by 1 packet of 10 sinusoidal full-phase pulses of welding current (I_2 = 12 kA, U = 0.69 V) of 50 Hz frequency in the first (minimum) stage of transformer power regulation of the 4 available, was taken as the reference mode. At transition from the soft to rigid mode MF intensity in the above frequency range rises approximately 2 times.

For objective evaluation of MF levels in all the available frequency ranges a new generalized index is proposed — the index of the exceeding level of the magnetic field (MF IEL)

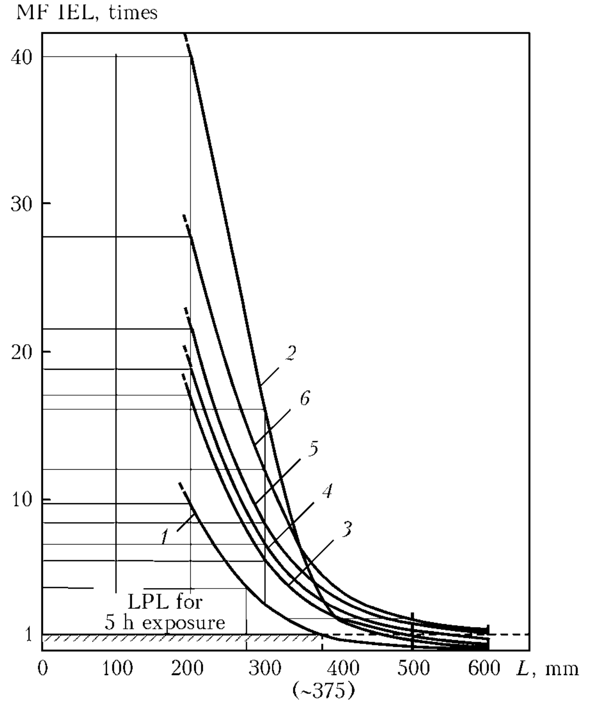

Figure 1. Dependence of MF IEL on distance to electrodes for spot welding machine MT-2202 and welding mode parameters in welder's work zone (in front of the machine) at height h = 1000 mm (in welded joint plane) from floor level (for designations see the text)

$$\text{MF IEL} = \sum_n \frac{H_n^2}{H_{n\,\text{LPL}}}, \quad (1)$$

where H_n is the actual MF intensity by frequency ranges n, A/m; $H_{n\,\text{LPL}}$ is the intensity of limit permissible MF levels by frequency ranges n, A/m.

Figure 1 shows as an illustration the characteristic experimentally derived dependencies of IEL of MF for 5 h exposure in front of spot welding machine of medium power on distance to its electrodes for different kinds of MF signals, where *1* — for 1 packet of 10 sinusoidal full-phase pulses of 50 Hz welding current with modulation of the leading and trailing edges (one half-period each) in the transformer minimum stage; *2* — same, but in the maximum stage; *3* — for angle of phase regulation of heating α_{ph} = 45° (pulse corresponds to curve *1*); *4* — for 1 packet of 10 pulses with 50 % modulation of packet leading edge; i.e. 5 first pulses from zero to amplitude value; *5* — for 2 packets of 5 pulses each with 2 period pause between pulses; *6* — for 2 packets of 5 pulses each with 100 % modulation of packet leading edges with 2 period pause between pulses.

Figure 2 shows a tentative spatial distribution of MF IEL in front of the welding machine in welding in the stringent mode of one packet of 10 sinusoidal full-phase pulses of 50 Hz welding current with leading and trailing edge modulation (one half-period each) in the transformer first stage. Obtained data are indicative of a considerable exceeding of magnetic radiation levels in the frontal and even more so in the profile area of welder work space.

As is seen from the data in Figure 1, any regulation of welding mode parameters (differing from the reference mode), enabled by the instrumentation, leads to increase of MF IEL in the working zone. MF IEL largest value is observed in front of the welding machine in horizontal plane xOy, passing through the welded spot and in this case — at 1 m height from the non-ferromagnetic floor. Having approximated the data of graphs in Figure 2 on the area of welder's head and feet, it was established that MF IEL in these regions is tentatively 4–6 times lower than at waist level. Calculation of MF IEL on the side of welding circuit in vertical plane zOy shows (Figure 2, *b*) that its spatial distribution in this region is similar to distribution in front of the machine, but in the horizontal plane it is 2–2.5 times higher, while remaining approximately the same in the area of welder's head and feet.

Analysis of the derived data shows that reliable provision of maximum effectiveness of

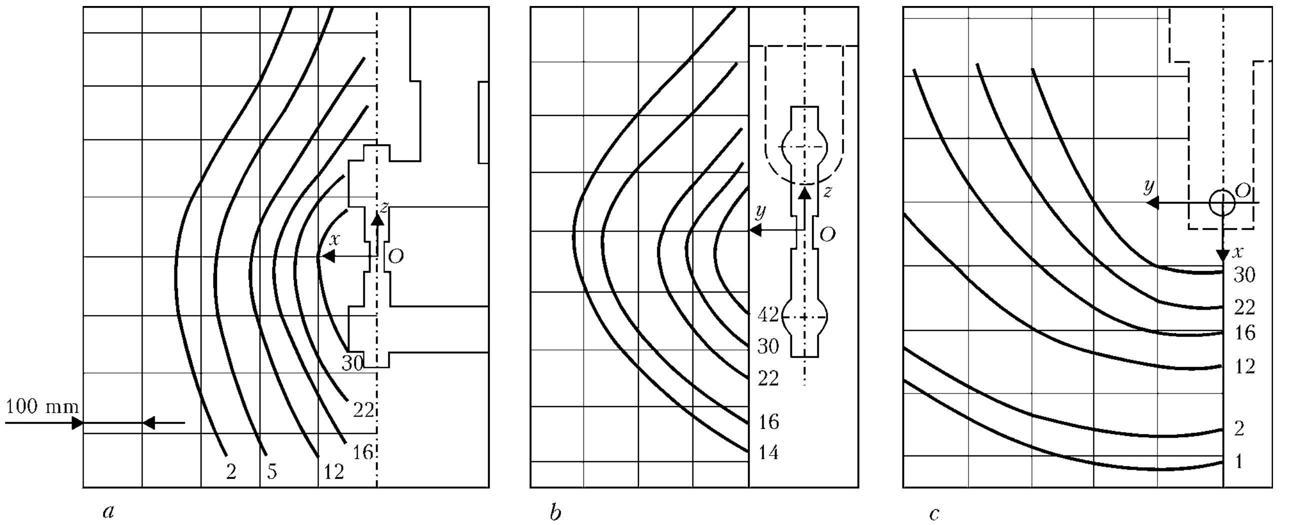

Figure 2. MF IEL distribution (for 5 h exposure) in plane xOz (a), yOz (b) and xOy (c)

welder's protection can be achieved by increasing the distance to radiation source or application of complete automation and moving the welder out of MF impact zone to not less than 1 m distance that is hardly feasible under the actual production conditions. Therefore, to resolve this situation and enable welder's operation of resistance spot welding machines in the frontal area, in the so-called manual mode, at distance $L \geq 150$–200 mm, the required effectiveness of protection E_{pr} from magnetic radiation should be not less than 60 to 40 times (see Figure 1). Required effectiveness of protection is determined by the following expression:

$$E_{pr} = H_{max} / H_l, \quad (2)$$

where H_{max} is the maximum value of MF intensity in the work place; H_l is the limit permissible value of MF intensity.

H_{max} value measured in welder's work place is used in E_{pr} calculation.

Development of protective gear for welders against electromagnetic radiation at operation of resistance spot welding machines in the manual mode, providing E_{pr} of the order of 100 times, should, apparently, envisage application of all the possible methods to lower magnetic radiation to the specified level [2], namely:

- protection by distance (up to $L_{min} \geq 250$–300 mm);
- protection by time;
- protection by optimization of welding modes, application of new welding processes with more acceptable physical parameters of electric current in sanitary terms and new principles of heat input regulation, when making the welded joint;
- shielding the current-carrying elements of welding circuit with preservation of maximum possible work space;
- application of individual protective gear;
- monitoring the magnetic situation in the work place by the welder himself using MF level detector.

Let us consider the capabilities of these methods.

Protection by distance. At operation of stationary spot welding machines in semi-automatic mode body parts the most loaded by MF are hands and arms, i.e. local body parts. Unlike the European sanitary norms, Ukrainian norms [2] do not specify application of local step-up factor for permissible level of MF intensity, equal to 2.5 at operation in pulsed MF, so that keeping hands at distance $L \leq 300$ mm from machine electrodes in the frontal area and especially in the profile area relative to machine welding circuit is inadmissible. Admissible distance to hands at operation should be the same as to the trunk. In this case application of such devices, as special technological fixtures, rotary tables, etc., as well as control panels with two interconnected buttons of welding switching on, ensuring minimum permissible distance, is a vital need.

Particularly negative consequences of MF impact on the welder are possible in operation with hand tools for resistance welding (tongs, spot welding guns and guns for impact capacitor-type stud welding) [3]. At 5 h exposure in this case MF IEL is higher than the norm approximately 400 times for hands and 100 times for head and trunk of the welder. Therefore, in hand tool design it is necessary to envisage not less than 250–300 mm distance from current-conducting parts of guns to their handles, and in case this leads to generation of considerable moments of inertia, it is necessary to fit the tool with a balancing device. Design and technological documentation should include the ergonomic component, i.e.

drawings, schematics of tool movement in space during operation, tool position in welding of each spot of the item, and its location relative to the body (head and trunk).

One can see, however, that at operation in the manual mode protection just by distance is insufficient.

Protection by time. Worker protection from electromagnetic radiation in different kinds of resistance welding is achieved through limitation of total time of the impact of MF, allowing for its spectral composition [2], on the welder during the work day by transferring him to other operations, not involving MF impact. Considering the real possible shortening of welder operation time (exposure time) to 2 h per shift, protection effectiveness with this method can be up to 2.5 times.

Protection by optimization of welding modes and welding process selection. Graphs shown in Figure 1 can provide some illustration of the method to improve the magnetic situation at the work places by mode optimization. Modes of spot (projection, seam, capacitor) welding can be regarded as quite diverse as to the obtained MF spectra, which is what determines the value of energy load on welder's body. Developers and manufacturers of new batch-produced equipment should take into account its application conditions and the acting sanitary norms, as application of this equipment in industry will be limited by levels of electromagnetic radiation in the working zone at its testing in the maximum power stage of welding transformer with different combinations of welding cycle regulator settings (see Figure 1). In the case of exceeding the specified levels of electromagnetic radiation and insufficient engineering capability for their lowering, production managers and welding equipment designers should apply additional measures for worker protection. For instance, the following engineering solutions can be applied in order to improve the magnetic situation around the hand tool:

- maximum limitation of welding modes by current (up to I_2 = 8 kA);
- welding performance in soft modes as far as possible, with one packet of full-phase sinusoidal current pulses with packet edge modulation (by one half-period);
- performance of heating power adjustment only by switching transformer power stages;
- connection of tools (tongs, guns, etc.) to a detached welding transformer by low-inductance (bifilar) cables.

The problem could also be solved by wider application of the technology of welding with gripper guns with remote control, when all the limitations on used welding cycle regulators, value and curve shape of welding current, and welding cycle pattern are eliminated, and high quality of welded joints is ensured. Research conducted at PWI shows that welding processes performed with rectified or pulsed rectified current of sufficient duration (several hundred milliseconds) have the best sanitary-hygienic characteristics. Therefore, it is recommended for welding technologists and welding equipment designers to thoroughly examine the possibility of application of resistance welding by rectified current, particularly in spot welding with hand tools.

Tentative lowering of MF energy load in the work places due to optimization of welding modes can be from 2 up to 10 times.

Shielding welding equipment and welder. At operation in the manual mode stationary shields, in addition to their functional purpose, should also meet two most important requirements: not to distort the nature of technological process, and not to lower significantly the labour efficiency.

It is important to satisfy the first requirement — not change the electric parameters of transformer secondary circuit, welding circuit, by introducing an additional resistance, that will lead to limitation of maximum welding current in it, and change of welding mode, respectively.

High labour efficiency can be actually ensured by free access to the welding site, preservation of the required dimensions of the work space for technological process performance, i.e. part mounting and removal, and prevention of additional operations with moving of the shield.

In terms of design and technico-economic characteristics, ferromagnetic materials (electric steel, carbon steel) are the most suitable material for manufacturing the shields for welding equipment. Specifics of welding equipment operation and design features of working electrodes and current-conducting buses do not allow application of the most efficient closed electromagnetic shields, but there is a possibility to install semi-closed shields, which are less effective.

Lowering of intensity of MF, generated by working elements and current-conducting buses of stationary spot welding machines, can be achieved using shielding devices (cylinder, closed shield, magnetic shunt), the effectiveness of which is from 2 up to 30 times. Shielding efficiency is understood to be the ratio of intensity (maximum value) in the work place H_{max} in the absence of the shield to intensity in the same point of the work place in the presence of the shield $H_{max\ sh}$:

$$E_{pr} = H_{max}/H_{max\ sh}. \quad (3)$$

E_{pr} is calculated using parameter H_{max}, measured in welder's work place at continuous operation of the transformer and permissible current:

$$I_{2\ ad} = I_{2r}\sqrt{\frac{DC}{100}}, \quad (4)$$

where I_{2r} is the rated welding current, A; DC is the duty cycle, %.

E_{pr} assessment by expression (3) is quite acceptable, although integral effectiveness of shielding pulsed MF by analogy with expression (2) and in keeping with the requirements of [2], is expressed as

$$E_{pr} = \sum H_n^2/H_{n\ LPL}^2. \quad (5)$$

Final check of shielding effectiveness is performed experimentally taking into account MF spectral composition by expression (5).

Dependence of MF IEL on distance to electrodes of spot welding machine MT-2202 (same current characteristic as in Figure 1) at shielding of welder body by an elastic shield in the form of an apron [4] is shown in Figure 3, where *1*, *3* — for 1 packet of welding current pulses at minimum and maximum power, respectively; *2* — with elastic shield of 2 continuous non-closed layers in welding at minimum power; *4* — behind elastic single-layer non-closed shield in welding at maximum power; *5* — behind elastic single-layer shield in welding at minimum power for 1 packet of welding current with phase regulation of heating α_{ph} = 45°; *6* — same, as in *5*, but without a shield.

In terms of design, shields mounted on working electrodes and current-conducting buses can have the shape of a parallelepiped or cylinder, made of carbon steel 2–3 mm thick.

Application of individual protection gear (hooded cloaks, aprons, capes, coats with trousers, etc.) developed for super high frequencies, becomes practically senseless in the low-frequency range, as the effect of reflection of electromagnetic waves for the material with net or cellular structure is lost.

Individual protective gear, for instance, continuous elastic magnetic shield with high magnetic permeability of magnetically-soft cobalt alloy of Co–Fe–Cr–Si–B alloying system with an amorphous structure in the form of welder's apron [4], complete with oversleeves, can be useful in certain situations at trunk shielding in local MF of medium intensity (up to 1500 A/m by the first harmonic) and should be regarded as the last resort for ensuring magnetic safety, as their effective operation requires preliminary lowering of MF levels to 1500 A/m; shortening of the time of MF establishment in a thin shield of limit thickness (0.015 mm) by increasing the steepness of rising edge of welding current pulses, that leads to increase of MF energy load in the area of welder's hands and head (in the region of welder's abdomen and chest shielding effectiveness can be from 2 up to 5 times (see Figure 3)); ensuring conditions eliminating contact with open current-conducting parts of welding equipment [2], as the elastic shield has a metal base.

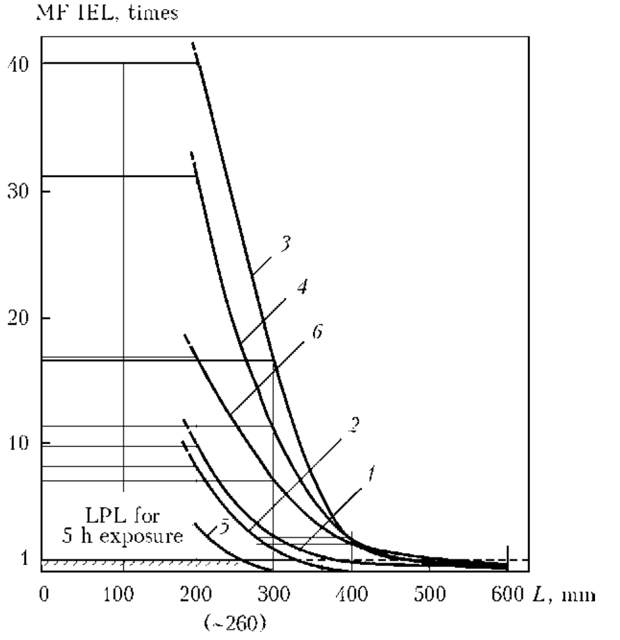

Figure 3. Dependence of MF IEL on distance to electrodes of spot welding machine MT-2202 at shielding of welder's trunk with an elastic shield in the form of an apron [4] (for designations see the text)

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